

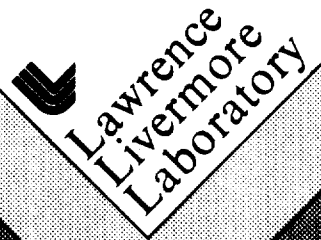
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ALTERNATE APPROACHES TO SYSTEM EMP  
RESPONSE ASSESSMENT

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ABSTRACT

The outlined assessment approaches of system EMP response as developed by LLL are based on either experimental low-level simulator excitation or surface current injection testing. The advantages and disadvantages compared to electromagnetic pulse (EMP) assessment techniques by other organizations are noted. Subthreat excitation of a full-scale system or of scale model on a transient electromagnetics facility is described. This assessment yields the linear external or internal response. A proposed procedure for surface current injection testing (SCIT) of either a full-size or scale model system at the subthreat level or a full-size system at the threat level is discussed. The full-threat testing enables assessment of the system nonlinear internal response. Some of the modeling errors involved in the assessment of EMP response of a real system in a threat environment are briefly discussed.

1. OUTLINE OF THE LLL APPROACHES

The LLL assessment approaches are based on transient measurements of the electromagnetic response of a full-scale system or scale model of it, either in a low-level simulator environment or subjected to either low-level or threat surface current injection testing (SCIT). The simulator field need not have the threat temporal waveform but only its spectral bandwidth. The injected surface current should have the proper spectral amplitudes (reduced, if desired, below threat level by an overall factor) at the first few resonant frequencies of the system. This approach is a deterministic one applied to one or just a few system samples rather than a probabilistic one.

The first LLL approach uses a transient electromagnetics facility and is described in Section 3. The simulator field is presumed known and of a plane wave or nearly plane wave nature. In the facility, either a full-scale system or a realistic scale model of it could be tested. Since the excitation is presumed to be subthreat level, only the linear external-coupling response

is studied. The equivalent circuit parameters are obtained in the frequency domain for antennas and cables at their points of penetration through the system envelope, and the electromagnetic pulse (EMP) response is deduced for "equivalent" linear internal loads at these points. Usually the "worst-case" response is studied, and the nonlinear response of sensitive internal circuitry would be computed from a separate internal circuit analysis. This approach accounts for the effects of apertures on the external surface current distribution flowing on the system and on the response of penetrating antennas and cables but does not account for direct aperture excitation of the system interior. This excitation and resultant response of the interior is ignored in this first LLL approach because it is a low-level linear response, whereas the nonlinear response of sensitive circuitry would be of interest.

The second LLL approach (Section 4) uses the SCIT of either a full-scale system or scale model of it. This testing uses the fact that the entire electromagnetic response of a system is usually overwhelmingly dependent upon the response of just a few ( $\leq 5$ ) natural modes of the system. If a full-scale system is tested with subthreat SCIT, or if a scale model is tested, the objectives of this approach are the same as for the first approach, namely deduction of the linear external coupling response of penetrating antennas and cables, from which the nonlinear internal response could be inferred. If, however, a full-scale system is tested at threat-level SCIT, the entire nonlinear response of the internal circuitry can (in principle) be measured.

Once the decision has been made to measure either a full-scale system or a scale model of it, the assessment could proceed in either of two ways. The first LLL method, employing testing on a low-level simulator facility (such as the LLL Transient Electromagnetics Range), yields the equivalent circuit (linear) at the ports where antennas and cables penetrate the system envelope. From this information, the linear EMP response of "equivalent" loads representing the interior circuitry may be computed. The second LLL method, using SCIT, requires measurement of the complex resonant frequencies of a few natural modes of the system, or its scale model, and computation of their amplitudes at threat or subthreat level. The direction and polarization of the incident wave\* can be accounted for by reciprocity. With this

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\*Unfortunately, the extrapolation from one environment to the other (i.e., airplane on the ground to one in free flight) remains as formidable as ever.

information and measurement of the network parameters at the open- or short-circuit ports where the current or voltage generators will be applied, the temporal generators may be designed to excite the natural modes exactly as the threat excitation would excite them (perhaps reduced by an overall factor). In this way, the linear external coupling of a full-scale or scale model system at subthreat level is replicated. Or the nonlinear internal response of a full-scale system at threat level may be measured.

After comparing the essence of either LLL approach to EMP assessment with the techniques of other organizations in Section 2, we will develop the details of both LLL approaches. Important problems of extrapolating for the various ports of entry (POE), correcting for different excitations, and extrapolating for environment will be discussed in Section 5.

## 2. COMPARISON WITH OTHER TECHNIQUES

### A. AIR FORCE WEAPONS LABORATORY

The Air Force Weapons Laboratory (AFWL) is concerned primarily with the estimation of the internal EMP response of aircraft in various spatial modes. In order to extrapolate from the measured response in a simulator-environment level to the EMP-environment level, AFWL has sponsored many analytical and some model (both wire-model and scale-model) studies for deducing extrapolation functions. Also external-internal coupling via penetrations such as cables and apertures has been analyzed, and transfer functions have been evaluated for various identifiable POE on the model B-1 aircraft.\*

Two major sources of error are apparent in this technique. The analytic and wire-model extrapolation functions for external coupling are not based on accurate scale models and are hence subject to modeling error, and the internal response has been analyzed by transfer function superposition instead of being measured in situ and scaled by the extrapolation of simulator-environment field to threat-environment field.

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\*Major POE can usually be identified, according to J.P. Castillo of AFWL in a classified document.

The LLL technique based on aircraft samples avoids the first source of error with either full-scale or realistic scale-model testing. The second source of error is the result of scaling from the ground plane simulator environment, with its limited angles of incidence, to free-flight threat environment with various angles of incidence and polarization of the EMP wave. This extrapolation error, to be discussed in Section 2.E and 2.F, is also present in the LLL assessment technique for evaluating free-flight EMP response.

#### B. BOEING AEROSPACE

Boeing's EMP assessment technique for ground facilities uses an electrical model of the system, the parameters of which are chosen from computations and measurements. In the PREMPT program, EMP coupling into a facility via antennas and cables is computed by computer codes (WIRANT, PRESTO), accounting for structure and shielding of the building. The flow of internal current to sensitive components is computed (PRESTO) with transmission line and network analysis.

The LLL viewpoint is that it would be preferable to excite the actual facility with a subthreat field, measure the currents at sensitive external-coupling points (ports), then measure the driving and transfer impedance at those ports, scale the equivalent linear electrical circuit, and compute the EMP spectral response. Nonlinear circuit analysis would then yield the response of nonlinear elements at the internal ports.

#### C. HARRY DIAMOND LABORATORY

The Harry Diamond Laboratory (HDL) technique of EMP coupling analysis (perfected for the Army's Multiple System Evaluation Program) requires validation of an assumed functional electromagnetic model of the system. Three computer codes are used for external coupling computations: TEMPO for antennas, NLINE for multiconductor transmission lines, and FREFLD for transmission-line cable response. The model parameters are adjusted until the frequency-domain, internal-measured response to a simulator agrees essentially with the response computed from the measured incident field. The model, as validated for worst-case response, is subsequently scaled, if necessary, to

represent a larger system and the EMP internal response computed according to the incident field spectrum.

This technique is similar to the first LLL approach except as regards modeling. Instead of assuming an electromagnetic model and validating its parameters by comparison of measured and computed internal responses, the LLL approach recommends measurement of the internal response of the real system at sensitive ports due to simulator field, measurement of the driving and transfer impedances at those ports, and determination of the linear frequency-domain equivalent circuit for all the coupled ports of interest. The nonlinear analysis would yield the EMP-driven currents in the sensitive nonlinear circuit parameters connected to these ports via cables and transmission lines.

#### D. MISSION RESEARCH CORPORATION

Mission Research Corporation (MRC) has evaluated external surface current and charge response of aircraft in a simulator field, both by a finite-difference computer code (THREDE) and by SCIT. The aircraft interior was isolated by a closed envelope.

Although the error in time-domain peak external surface current response has tended to be 6 dB for SCIT as compared to  $\approx 3$  dB for the finite-difference code, the LLL approach favors the former. We believe the error in the SCIT technique can be reduced, even when evaluating the EMP internal response of a real system. The finite-difference computations alone are not appropriate for wire and/or aperture coupling into the complex electromagnetic interior of an aircraft.

#### E. ROCKWELL INTERNATIONAL

The objective of the Rockwell assessment technique for aircraft is to obtain confidence intervals (reliability and its confidence level) for an internal pin (i.e., component) safety margin. Margin is the dB excess of threshold current over threat current induced.

The full-size system simulation test is performed and various internal pin-wire currents are measured. Aside from measurement and data processing errors, extrapolation errors occur in deriving internal EMP-excited currents

from their simulator-excited values. In the Rockwell extrapolation method 1, computer modeling error occurs because the extrapolation ratio is computed from a stick wire model of the aircraft. Its extrapolation method 2 avoids this by deriving the ratio from University of Michigan scale model data. In addition, Rockwell included a POE error for each wire current, which is inherently present for two reasons: (1) extrapolation from simulator-ground plane environment to threat-free flight environment requires computed extrapolation factors for the geometry difference and different angles of incidence and polarization, and (2) the relative importance of the various POE is considered unknown.

The LLL approach would avoid extrapolation method 1 and its inherent modeling error and use method 2, with the real aircraft preferred to a scale model. And the approach would avoid the POE error described above if the aircraft were parked on the ground and the response for grazing incidence (and perhaps various azimuthal angles) were of interest. The question arises as to whether there would be any advantage in using the LLL approach to infer internal aircraft response under free-flight conditions from ground-excitation response for a variety of threat incident angles and polarizations.

Let us consider the extrapolation from ground plane, simulator conditions to free-flight, more general excitation, in two stages: (A) extrapolation from simulator (grazing) excitation to free-flight incidence and polarization with the aircraft on the ground, and (B) extrapolation from ground plane geometry to free-flight geometry. These extrapolations are unfortunately interrelated. Now the LLL approach offers a way to avoid extrapolation (A)--by employing the reciprocity concept. This will be described in Section 4; the idea is to evaluate the response of an internal port to an above-ground incident EMP wave launched by a distant dipole by interchanging source and response--put a known source generator at the response point and measure the distant field with a small pickup probe at the position of the EMP dipole. This is usually not practical because the known source generator at the internal port would have to be strong enough to create measurable distant field beyond the aircraft and this would probably disrupt the internal circuitry. However, the same objection is not valid for SCIT excitation because the EMP reference response points are on the external surface envelope, where source generators would be placed for reciprocity purposes. In other words, reciprocity considerations could enable one to replicate the

EMP surface current response of the important natural modes\* and hence the EMP response of the interior as well.

Our conclusion is that the LLL approach with SCIT excitation could be used to evaluate EMP system response, internal as well as external, for any threat wave incident above ground on a system, but would not obviate a need for extrapolation (B) from ground-plane geometry to free-flight geometry; i.e., correct for the absence of the ground plane. Such extrapolation by computer code would of necessity have to allow for ignorance in the relative importance of the POE; i.e., average the system response over the various possible POE, as, for example, in the Rockwell methodology.

#### F. TRW CORPORATION

TRW considered four basic extrapolation methods of obtaining an EMP response at sensitive internal points of a system: (1) direct scalar extrapolation from simulator to threat field with the system absent, (2) by a hybrid analytical-empirical model, (3) analytical model prediction in which the model is adjusted until computed simulator response agrees with measured response, whereupon the latter is scaled to threat level, and (4) by low-level excitation to discover the sources of EMP penetration, followed by simulator excitation of these sources one by one to determine the net internal response.

In TRW method (2), if surface current  $J_s$ , for example, were the extrapolation parameter, a linear internal wire response  $I_w$  in the frequency domain would be computed as  $I_w^{\text{threat}} = J_s^{\text{threat}} \times (I_w/J_s)^{\text{sim}}$ , where  $J_s^{\text{threat}}$  is the analytically derived quantity and the  $(I_w/J_s)$  is empirical.

The TRW method (4) could be used to extrapolate from test environment to threat environment (from an aircraft parked on the ground to one in flight, for example), as follows. The linear transfer functions from the various POE (assumed known) to the sensitive internal points could be found in the test environment. Then the surface current at each POE could be scaled linearly by computer code from test to threat environment. The linear combination of the same transfer functions times the threat surface currents would then yield a

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\*There is an implied assumption that the SCIT modes are very weak functions of the internal circuitry.

reasonable approximation to the threat internal currents. Unfortunately, this procedure gives only an indication of the upset of the nonlinear circuits, not their detailed behavior.

The first LLL approach avoids analytically derived parameters unless absolutely necessary, as, for example, the extrapolation ratio  $(J_s^{\text{free-flight}}/J_s^{\text{ground}})$  computed in the absence of any free-flight data. In either version of the LLL assessment technique, the frequency-domain equivalent circuit parameters would be obtained directly from measurements of the network parameters of the equivalent circuit for the external or internal port(s) of interest. Then the circuit would be scaled in geometry and frequency, if necessary, to represent the full size system, in which the applied EMP waveform would determine the threat response.

The TRW scalar extrapolation method (1) would be implicitly included but no extrapolation by method (2) unless absolutely necessary to convert from simulation to threat environment. The analytical model prediction method (3) is similar to the LLL equivalent circuit determination; the latter involves the absolute minimum number of network parameters necessary (which are frequency dependent). Regarding TRW extrapolation method (4) to determine net internal threat response (nonlinear), the LLL assessment method with threat level SCIT would enable direct evaluation of the resultant internal response in its test environment.

### 3. DETAILS OF THE LLL APPROACH USING A TRANSIENT ELECTROMAGNETICS FACILITY

We assume a threat current  $I_w$  is required at the point where a cable or antenna penetrates the system envelope. We position the system, or the best scale model of it allowed by practicality, in a facility (such as the LLL Transient Electromagnetics Range) so as to preserve the external environment as accurately as possible. Any extrapolation from the facility environment to another without measurements in the latter would require a computed frequency-domain extrapolation factor. Even the extrapolation from an aircraft parked on a perfect ground plane to the aircraft in free-flight is not trivial because of the image interaction in the former case.

In the facility, the (antenna) input impedance  $Z_I(f)$  is measured at the penetration point or port. This may be done accurately and rapidly with a time-domain reflectometry (TDR) technique as described by Ref. 1. Then the effective height  $h_e(f)$  is measured in a scattering experiment, which is also efficiently performed in the time domain, relative to a calibrated  $E_o^{inc}(f)$  at a convenient reference point. These two parameters,  $Z_I$  and  $h_e$ , embody the entire linear electrical effect of the system and surrounding environment on a load connected to the port terminals. Parameter  $h_e$  strictly depends on polarization and physical waveshape of the incident electric field. However, two independent  $h_e(f)$  parameters can be defined in the circuit for two orthogonal polarizations of  $E^{inc}$ . Regarding waveshape, we have found<sup>2</sup> for simple systems that curvature of the incident field lines has surprisingly little effect ( $\leq 1$  dB) on the so-called level-A responses of load energy dissipated, peak load current, etc., generated by a double-exponential EMP wave. Consequently, we believe this source of error will be negligible in EMP assessment of most practical systems, but further quantification will be necessary for such complicated systems as ships, aircraft, and ground installations.

After the equivalent circuit  $Z_I$  and  $h_e$  are found, they are scaled, if necessary, to represent a full-size system. The scaling rules are simple<sup>1</sup> and rigorous, provided the surface conductivity is sufficiently high and volume conductivity is negligible. Then the threat waveform  $E^{th}(f)$  is applied. The voltage  $E_o^{th}(f)h_e(f)$  drives current through  $Z_I(f)$  in series with a load  $Z_L(f)$  of interest and  $I_w^{th}(f)$  is obtained. Inverse Fourier transformation of this current yields  $I_w(t)$ . Of course, time-varying load energy absorbed, load spectral power, etc., may all be computed.

In fact, HDL tested this very procedure<sup>3</sup> on a UHF antenna configuration and predicted the simulator-induced load current within a factor of about 2 (6 dB). Our experience on the LLL Transient Electromagnetics Range indicates that an overall experimental plus data processing error of  $\leq 4$  dB is reasonable. It is necessary to keep the measuring system noise low so as not to corrupt  $Z_I(f)$  and  $h_e(f)$  near their resonant frequency. The above evaluation of EMP response at one port is based on known loading at other

ports. If we wished to study EMP response as a function of loads at two ports, for example, we would first determine the network parameters  $Z_{ij}$  and  $h_{ei}$  in the coupled equations

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + h_{e1} E_o^{inc}, \quad (1a)$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 + h_{e2} E_o^{inc}, \quad Z_{21} = Z_{12}. \quad (1b)$$

$Z_{11}$  and  $Z_{22}$  would be measured at one port with the other open-circuited;  $Z_{12}$  would be measured as  $(V_1/I_2)_{I_1=0}$ ; and the  $h_{ei}$  would be measured separately in one scattering open-circuit experiment. Then the linear threat response could be obtained for loads  $Z_{L1}(f)$  and  $Z_{L2}(f)$  by solving Eq. (1) with  $V_1 = -Z_{L1}I_1$ ,  $V_2 = -Z_{L2}I_2$ , and  $E_o^{inc} = E_o^{th}$ .

#### 4. DETAILS OF THE LLL APPROACH USING SCIT

The preceding technique for assessing the linear external coupling response of a system to EMP might prove inconvenient if a large number  $N$  of internal points (ports) are involved. Or the nonlinear internal response as a result of simulated threat excitation might be desired. To obviate the necessity of evaluating  $N$  different  $h_e$  and  $Z_{ii}$  and of data processing the responses of  $N$  different equivalent circuits\* to threat excitation, we can take advantage of the fact that in the threat spectrum relatively few natural modes of the entire system are excited. This means the entire, external and internal, current response of a system can be simulated by appropriate current injection of the correct frequency content by just a few generators connected

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\*The  $Z_{ij}$  in Eq. (1) are not required because we assume the response of each port with known loads at the other ports is to be found.

externally. SCIT can be performed on actual systems, or scale models, at subthreat level, and the responses scaled to obtain full-size system threat response on the external envelope. Since a natural mode is characteristic of the entire system, the excitation point for it is not critical.

SCIT has been employed or considered for a number of projects to date: HDL, supported theoretically by JAYCOR Corp., on the Skynet satellite; TRW, supported by the computer modeling at Mission Research Corp. (MRC), on a model of a space satellite with two booms; Dikewood Corp., under contract to AFWL, on the EMP response of long VLF/LF wire antennas trailing from aircraft; HDL on cable systems; and Naval Surface Weapons Center (NSWC) on aircraft skin current response.

An outline of the steps in the LLL approach of using SCIT is as follows:

- (1) Measurement of the complex natural frequencies of the system of interest in its environment.
- (2) Calculation of the amplitudes of those natural modes<sup>\*</sup> within the plane wave spectrum excited by threat. For many systems, the number of strongly excited modes is limited to  $\leq 5$ .
- (3) Selection of the open- or short-circuited ports on the external surface where the modes can be efficiently excited.
- (4) Determination of the natural mode response (amplitude and phase) to threat at each port by use of reciprocity: excite the port by a temporal generator  $J_g$  (electric current) or  $M_g$  (magnetic current or voltage source), measure the radiated field in the direction of the incident threat (and with the same polarization) by small antenna pickup and use one of the following reciprocity relations:

$$\int \bar{E}^{th} \cdot \bar{J}_g \, dv = \int \bar{E}_g \cdot \bar{J}^{th} \, dv \quad (\text{for } \bar{E}^{th}) , \quad (2a)$$

$$\int \bar{H}^{th} \cdot \bar{M}_g \, dv = \int \bar{H}_g \cdot \bar{M}^{th} \, dv \quad (\text{for } \bar{H}^{th}) . \quad (2b)$$

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<sup>\*</sup>We assume the mode properties negligibly depend on the internal circuitry; in particular, its nonlinear properties under threat excitations.

These relations and the measurements of  $\bar{E}_g$  produced by  $\bar{J}_g$  or  $\bar{H}_g$  produced by  $\bar{M}_g$  will determine the frequency spectrum of  $\bar{E}^{th}$  (caused by  $\bar{J}^{th}$ ) or  $\bar{H}^{th}$  (i.e.,  $I^{th}$  caused by effective magnetic source  $\bar{M}^{th}$ ) at the ports.

Note that one antenna pickup in the direction of the incident threat wave will serve for excitation at all the ports.

- (5) Measurement of the Z- or equivalent T-network parameters of the system at its external ports and at the natural frequencies of importance. This involves Laplace transformation of the temporal data.
- (6) Evaluation of the injection generator waveform at each port to obtain the same natural mode response as found in step (4) for the threat (perhaps reduced by a convenient factor). This is greatly simplified if each generator is designed to have a waveform  $Ae^{-\alpha t} \cdot \sin(\omega t)$  where  $\alpha + j\omega$  is close to the natural frequency of just one of the modes excited.

The mathematical details of this approach are included in the Appendix.

Once the proper injection generators are exciting the ports, the internal response will be correctly measured at the threat level, except perhaps for the convenient reduction factors mentioned in step (6).

We have assumed the full-scale system has been treated by SCIT. A scaled-down model could be treated instead, subject to possible modeling errors. The SCIT procedure will then be based on the scale model, subject to an EMP spectrum scaled up in frequency by the geometrical reduction factor, and the final SCIT-induced external response would be scaled down in frequency to obtain the external response of the full-scale system.

Some problem areas exist for SCIT, but they are not insurmountable. Coupling between SCIT generators could be largely obviated by designing them for different resonant frequencies, approximating the natural mode resonances of importance. Coupling between the SCIT generators and the system perturbs somewhat the natural modes but can be minimized by connecting low-impedances

voltage generators to the body by long, low-impedance cables and by minimizing the size of capacitor plates which couple a high impedance current generator to the body. Some perturbation is inevitable, but if the coupling occurs far from antennas, apertures and inadvertent POE it should be negligible. Generator jitter in time base and amplitude can be reduced by averaging over repetitive discharge cycles. Determination of the complex natural frequencies by data processing temporal response data can be done accurately by the Prony technique.<sup>4</sup> Data processing error caused by proximity of a generator complex frequency (damped sinusoid) to a natural mode resonant frequency can be minimized by accurate measurement of the latter with the inactive generator in place and by repetitive averaging over generator cycles.

Finally, the problem of extrapolating internal system threat response  $I_w^{th}$  in one environment to that in another environment can only be performed with a computed extrapolation ratio (see the discussion in Section 2.E).

$$I_w^{th}(s_\alpha^{th}) = J_s^{th}(s_\alpha^{th}) \times (I_w/J_s)_{s_\alpha^{sim}}^{sim}, \quad (3)$$

where  $s_\alpha^{th}$ , the  $\alpha^{th}$  normal mode resonant frequency in threat environment, is a perturbation of  $s_\alpha^{sim}$ , the corresponding normal mode in the simulator environment. Fortunately, a computer code (NECS) exists at LLL for computing  $s_\alpha^{th}$  and  $J_s^{th}(s_\alpha^{th})$  of thin-wire and surface-plate representations of a solid body in a simple environment--in free space or on or above a perfect or imperfect ground plane.

## 5. MODELING ERRORS

Any EMP threat assessment procedure such as the LLL approaches herein advocated suffers inevitable modeling error when the system of interest is replaced by a scale model. Usually the internal circuitry cannot be modeled so one must compute the external surface current response or the response of equivalent loads on cables and antennas where they penetrate the system envelope. The linear internal response is then inferred from this response considered as known excitation of the interior and circuit analysis. Care must be taken to infer the nonlinear threat level internal response.

The extrapolation of EMP response from one environment to another via a computed ratio has been discussed in Section 2.E. There it was concluded that the LLL approach could extrapolate the EMP response to different threat incident angles and polarizations but could not improve on conventional treatments of the POE uncertainties when deducing EMP response in one geometry from the measured (or computed) response in another geometry.

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## APPENDIX

### THE MATHEMATICS OF SCIT

Consider a conducting body with a long wire appendage as shown in Fig. A-1. It is excited by an EMP plane wave, generated either by the electric dipole  $I^E(t)\bar{d}^E$ , which excites open-circuit voltages such as  $V_A(t)$  at port (A), or by magnetic dipole  $I^{E*}\bar{d}^E$ , which excites short-circuit currents such as  $I_B(t)$  through port (B). The problem is to design current generator  $I_A^e(t)$  and voltage generator  $V_B^e(t)$ , etc. to excite the body in the same way. The details of the six steps outlined in Section 4 are as follows:

- (1) The natural frequencies of the modes,  $s_i$ , in the EMP spectral range are found by exciting the body at any convenient point, say port B, by an appropriate generator,  $V_B(t)$ , at port B, such that all these modes will be excited. The response at any convenient point, say  $V_A(t)$  (in the absence of  $I_A^e$ ) when processed by the Prony technique will yield the  $s_1, s_2, \dots, s_N$  of interest.
- (2) The EMP spectrum at each  $s$  is obtained as:

$$I^E(s_i) = \int_0^\infty I^E(t)e^{-s_i t} dt \quad (\text{Laplace transform})$$

and similarly for  $I^{E*}(s_i)$ .

- (3) The ports A, B, ... for exciting the  $s_i$ -modes must be chosen judiciously, with some knowledge of their qualitative behavior. For example, if  $s_1 = \alpha_1 + j\omega_1$ , and  $\omega_1$  has a wavelength  $\sim 2L$ , then surely this mode can be excited at port B located at the wire center.
- (4) Determine the open-circuit voltages such as  $V_A(s_i)$  and short-circuit currents such as  $I_B(s_i)$  excited by the EMP. A good way to do this is by reciprocity between port and EMP source. By placing an electric dipole at the source of the EMP to measure  $\bar{E}_{\text{rad}}(t)$  radiated by  $I_A(t)$  and decomposing those into components at  $s_1, s_2, \dots$ , as in (2), one can obtain  $V_A(s_i)$  as\*

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\*This and the following reciprocity relations may be derived rigorously.

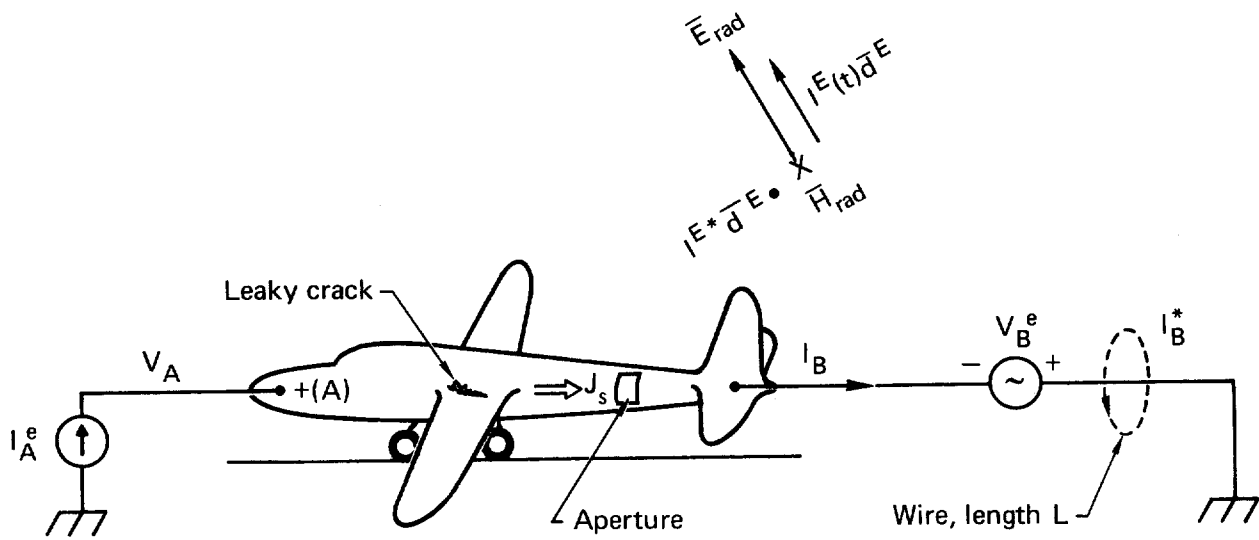


FIG. A-1. The conducting body excited by an EMP wave represented either by electric dipole  $I \vec{d} E$  or magnetic dipole  $I \vec{d} E$ . Representative ports A and B are shown, where the EMP response will be simulated by external generators  $I_A^e$  and  $V_B^e$ .

$$V_A(s_i) = \frac{I_A^E(s_i) \bar{d}^E \cdot \bar{E}_{rad}(s_i)}{I_A(s_i)} .$$

Analogously, by placing a circular loop to measure  $\bar{H}_{rad}(t)$  radiated by  $\bar{J}_B^*$  (a voltage source) and decomposing these into components,  $s_1, \dots$ , one can obtain  $I_B(s_i)$  inducted by the EMP as

$$I_B(s_i) = \frac{I_B^{E*}(s_i) \bar{d}^E \cdot \bar{H}_{rad}(s_i)}{J_B^*(s_i)} .$$

- (5) The next task is to relate the EMP responses of (4) to the generator where

$I_A^e, V_B^e, \dots$ , via the port equations

$$V_A(s_i) = Z_{AA}(s_i) I_A^e(s_i) + T_{AB}(s_i) V_B^e(s_i) + \dots,$$

$$I_B(s_i) = T_{BA}(s_i) I_A^e(s_i) + Y_{BB}(s_i) V_B^e(s_i) + \dots,$$

where  $Z_{AA}(s_i)$ , for example, must be measured under the conditions of these equations; i.e.,  $V_A(s_i)/I_A(s_i)$  with other open-circuit ports open and all short-circuit (voltage generator) ports shorted. This can be done in the time domain with any reasonable current generator  $I_A(t)$ .

The inversion of this simultaneous set of equations at each  $s_i$  yields the desired equivalent generators  $I_A^e(s_i), V_B^e(s_i), \dots$ .

- (6) The final step in the simulation is to synthesize each generator, such as  $I_A^e(t)$ , to have the same spectral content  $I_A^e(s_1) + I_A^e(s_2) + \dots$ . This problem is enormously simplified if each generator can be designed to have a decaying waveform with a spectrum large near one of the  $s_i$ . For example  $I_A^e(t) \approx e^{-\alpha' t} \sin \omega' t$ , where  $-\alpha' + j\omega' \approx s_1$ . If this can be done, the set of equations in (5) can be solved to good approximation by

$$\left. \begin{array}{l} V_A(s_1) \simeq Z_{AA}(s_1) I_A^e(s_1) \\ \text{or } I_B(s_1) \simeq T_{BA}(s_1) I_A^e(s_1) \end{array} \right\} \text{ for } I_A^e,$$

and similarly for the other generators, each with a spectrum large near only one of the  $s_i$ . The spectrum of  $I_A^e(t)$  above is, by Laplace transform

$$I_A^e(s) = \frac{\omega'}{(-\alpha' + j\omega' - s)(-\alpha' - j\omega' - s)},$$

large at  $s = s_1 \simeq -\alpha' + j\omega'$ .